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The decay and interruption of interactions between search mechanisms

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Abstract

The attentional mechanisms in the brain responsible for fast pop-out search and slower difficult search have been shown to interact. Even if pop-out search is interrupted, by the addition of extra distractors to an initially simple search display, the partial computations calculated by the mechanisms responsible for pop-out can facilitate subsequent difficult search ("search assistance"; Psychon. Bull. Rev. 7 (2000) 292; Vision Res. 40 (2000) 891). With the present experiments, we aimed to discover whether search assistance is disrupted when the display that affords pop-out search disappears before the appearance of the display that must be examined by difficult search. Search assistance was not disrupted by the insertion of a blank screen in between the first and second portions of the display (Experiment 1). Search assistance for target-present trials was not disrupted by the insertion of black disks in between the first and second portions of the display (Experiment 2), but this manipulation did disrupt search assistance for target-absent trials. Implications for the relationship between search assistance and visual marking of distractors (Psychol. Rev. 104 (1997) 90) are discussed. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The human visual system is confronted with an overwhelming amount of information, and it selects only a limited subset for detailed analysis. The mechanisms responsible for this selection must operate quickly so that people can respond adaptively to changing environments. Researchers use data from search tasks to investigate the mechanisms responsible for visual selection. In a visual search task, observers determine whether or not a target item appears among distractors (other items) in a display. Researchers classify search performance in terms of response time (RT) patterns. In pop-out search, RTs are fast, and RT for correct responses is virtually independent of the number of items in the display. In difficult search, RTs are much longer and generally increase linearly with the number of items (Treisman & Gelade, 1980). Pop-out search is possible when the target differs from the distractors in simple ways. Many researchers believe that early "preattentive" mechanisms in the brain perform pop-out search in parallel across the entire display; difficult search occurs when the display is too complicated for pop-out mechanisms to detect the target and "attention" is required (Treisman & Gelade, 1980; Wolfe, 1994).

Do fast, preattentive selection mechanisms interact with slower, attentive selection mechanisms? Olds, Cowan, and Jolicoeur (2000a,b) developed a technique to first interrupt fast selection before it has a chance to complete, and then to determine whether the intermediate computations that had been calculated by these fast selection mechanisms influence other, slower selection processes. Their results showed that even when pop-out search fails to detect a target, its *partially completed computations* can be used to assist other, slower search processes—that is, pop-out and difficult search interact.

In an experiment typical of this work (Olds et al., 2000a,b), observers reported the presence or absence of a target, seen among distractors (see Fig. 1(a)). The target was a disk of a particular colour; the distractors

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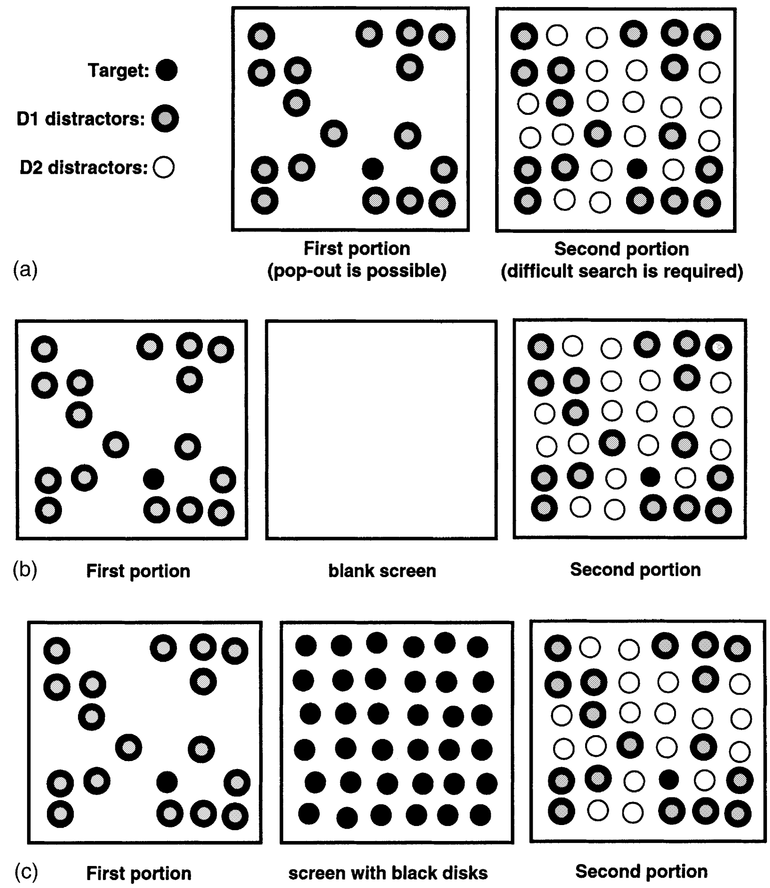

Fig. 1. (a) The general sequence of displays in a trial in the Olds et al. (2000a,b) experiments. The first portion of the display appears. Then, after the delay (SOA), the second set of distractors is added. In the experiments, display items were coloured disks equiluminant with the gray background (the target was orange, the D1 distractors were pinkish orange, and the D2 distractors were yellowish orange); they are depicted here as grayscale disks with varying border thicknesses (corresponding to different colours) for illustration purposes only. (b) Experiment 1: a trial with a blank screen between the first and second portions of the display. (c) Experiment 2: a trial with black disks appearing between the first and second portions of the display.

were disks of different colours (D1 and D2). Each trial began with a central "+" which the observer was asked to fixate, followed by a blank interval and then the stimulus. The first portion of the stimulus presented the target (on 50% of trials) along with distractors of one colour (D1). Pop-out search is possible for such stimuli. After a delay (stimulus onset asynchrony, or "SOA"), distractors of a second colour (D2) were added. D2 was chosen so that the target colour was between D1 and D2 in colour space; pop-out search is not possible for this type of display (Bauer, Jolicoeur, & Cowan, 1996; D'Zmura, 1991; but see Rosenholtz, 1999). The SOAs for a typical experiment were 0, 50, 100, 150, 200, 250, 300, 1000, and ∞ ms (in the ∞ ms condition, the D2 distractors never appeared). The appearance of the second set of distractors prevented *further* pop-out processing, so difficult search was required to find the target. Because the D2 distractors prevented pop-out processing without masking the existing display (they appeared in initially empty locations only), difficult search could proceed after they were added. Therefore, in addition to interrupting pop-out search, these distractors also acted as a probe to examine the influence of incomplete (interrupted) pop-out search on difficult search (i.e., an interaction between the mechanisms responsible for these two kinds of visual selection). Note that if the target was present in the first portion of the display, it was also present in the second portion; if the target was absent from the first portion of the display, it was also absent from the second portion. That is, the information required for correct response was always present from the beginning of stimulus presentation.

Difficult search and pop-out were measured by the following control conditions: SOA $= 0$ was pure difficult search (target, D1, and D2 items appeared simultaneously); SOA $= \infty$ was pure pop-out search (only the target and D1 items appeared; D2 distractors never appeared). Examination of the RT distributions for conditions with different SOAs showed that partial pop-out computations assist difficult search (Olds et al.

(2000a,b) described the technique for measuring this interaction). The facilitation of difficult search by partial pop-out computations, or "search assistance", has been demonstrated not only for search for targets defined by colour, but also for orientation search (Olds, Cowan, & Jolicoeur, 2000c) and for conjunction search (search where the target is defined by the conjunction of two features, e.g., colour and shape; Olds, Jolicoeur, & Cowan, 2001).

Several additional results shed light on the nature of the information that pop-out transmits to difficult search. If the target is moved to another location when the second set of distractors is added (at the SOA), partial pop-out does *not* assist difficult search (Olds et al., 2000b, Experiment 7). This result shows that search facilitation, when it does occur, involves information about target location, i.e., where the target *is*. (Otherwise, changing the target location would not eliminate the effect.) However, results from target-absent trials mirrored those from target-present trials—that is, partial computations by pop-out mechanisms assisted difficult search on target-absent trials, in experiments where the target did not move, but they did not in experiments where the target moved. These results indicate that perhaps search assistance involves transfer of information about where the target *is not*, for example, locations that have been determined to contain distractors. Finally, more recently Olds, Punambolam, and Degani (2001) have found evidence that search assistance involves the transmission of information about where the target *could be*. That is, encoding of initial item locations may occur during the first portion of the display (in addition to the processing that determines the colour of each item and its match to the desired target properties). It may be this location information that is transmitted to difficult search—information about initial item locations would be useful for subsequent difficult search because in experiments where the target does not move mid-trial, difficult search needs only consider those initial item locations (the target will be in one of those locations if it is present). This would be a sort of spatial cueing effect (Palmer, 1995). Note that information about where the target could be (which is useful on both target-absent and target-present trials) is different from information about where the target is (which only exists on target-present trials).

Another set of search experiments has investigated the representation of locations known not to contain the target. Watson and Humphreys (1997) have investigated the transfer of information from the processing of one display to the processing of a subsequent, related display, in a different way from the technique of Olds et al. (2000a,b). They presented observers with a conjunction search condition and a feature search condition. In a third, "gap" condition, one set of distractors (green Hs) appeared for 1000 ms. Then after a delay the second set of distractors (blue As) were added, along with the target (a blue H), on 50% of trials. The target, when present, appeared with the second set of items—this is different from the experiments of Olds et al. (2000a,b), where the first portion of the display contained the target (i.e., it was informative). Search in Watson and Humphreys' (1997) gap condition was as efficient as feature search, and was more efficient than conjunction search. This efficient gap search occurred even though the informative portion of the gap display was identical to the conjunction search display (and therefore one might expect gap condition efficiency to be low). This surprising efficiency occurred even if eye movements were prevented, but it required at least a 400 ms presentation of the initial distractors. In addition, gap search was not efficient if luminance changes occurred along with shape changes at old distractor locations (Experiment 4), and efficiency was reduced if an attention-demanding task had to be performed concurrently with the gap search task (Experiment 8). Watson and Humphreys (1997, 1998, 2000) proposed that observers can ignore old items (the initial distractors) by a spatially parallel top-down process of inhibition of the locations of these items, which they called "visual marking".

In another experiment (Experiment 6), Watson and Humphreys (1997) tested whether inhibition of return (a decrease in processing ability at recently attended locations, "IOR"; Posner & Cohen, 1982) was responsible for the marking effect. They showed the initial green H distractors for 750 ms, then the display disappeared for 250 ms, and then the whole conjunction display appeared. Watson and Humphreys argued that if IOR was the basis for visual marking, then the initial items should be inhibited as usual. However, visual marking disappeared when the items disappeared for 250 ms, that is, gap search was inefficient in this experiment. Something about item disappearance eliminated the inhibition.

The results of Olds et al. (2000a,b) have indicated that search assistance could be based on information about where the target *is not*, and thus it is possible that visual marking could underlie the search assistance effect (because visual marking provides information about where *not* to search). This suggestion seems counterintuitive at first: visual marking has been shown to consist of top-down *de*-prioritization of "old" items (Watson & Humphreys, 1997), and in search assistance the observer *prioritizes* those old items. However, a role for marking is plausible: perhaps during the first portion of the display, the visual system determines that some of the initial items are distractors rather than the target. Although pop-out search occurs in parallel, it is likely that because there is noise in the system different distractors are rejected at different points in processing. In the Olds et al. (2000a,b) experiments, on some trials this process was interrupted before completion. It is possible that search assistance consists of transmitting, to difficult search, information about which items have been determined to badly match the target features. Note that an indication of where the target is not located would be helpful to difficult search on both target-present and target-absent trials. Watson and Humphreys (2000) also showed that marking occurs only when it is advantageous and helps the observer; this would be the case in experiments of the form illustrated in Fig. 1(a).

Watson and Humphreys (1997) showed that full marking requires 400 ms; however, it is possible that *partial* marking could cause search assistance. Furthermore, it is possible that it would be too difficult to simultaneously mark items and search them during the first portion of the display (note that in Watson & Humphreys' (1997) experiments, the observer never had to search the initial items while marking them—the target was never one of the previewed items). Given these questions, Experiment 1 was designed to test whether the mechanisms responsible for visual marking could be contributing to search assistance.

2. Experiment 1

We inserted a blank screen between the first and second portions of the display (Fig. 1(b)) to investigate whether search assistance could be based on visual marking. That is, all items disappeared between the portion with the target and D1s, and the portion with the target, D1s, and D2s. Watson and Humphreys (1997) found that a blank screen eliminated visual marking in their gap condition. If visual marking is responsible for search assistance, then insertion of a blank screen mid-trial will eliminate search assistance.

Another question was whether search assistance would decay with time. We aimed to measure the timecourse of search assistance—how long does the partial pop-out information last? Perhaps failed pop-out will help difficult search only within a narrow time window. Or, alternatively, perhaps any interruption at all (even only one screen refresh, 13 ms) will eliminate search assistance—Rensink, O'Regan, and Clark (1997) have shown that some kinds of perceptual processing are greatly hampered by the insertion of blank screens between different portions of a display. If search assistance requires the continuous presence of the initial items, any interruption will eliminate it.

In Experiment 1a, we used a blank screen of 107 ms. Because Watson and Humphreys (1997, Experiment 6) used a duration of 250 ms, for the gap between the first and second portions of their display, we used a gray-screen duration of 253 ms in Experiment 1b. Another motivation for using longer gray-screen durations in Experiment 1b was that our stimuli are equiluminant (unlike Watson and Humphreys' stimuli), and colour processing occurs more slowly than luminance processing. Therefore Experiment 1b also included a gray-screen duration of 507 ms, presented intermixed with the 253 ms gray-screen duration. In addition, perhaps at such a long delay the information required for assistance would have decayed—one might expect to find search assistance on trials with a short gray-screen duration but not on trials with a long gray-screen duration.

Note that although Watson and Humphreys (1997, Experiment 6) displayed the initial portion of their stimuli (distractors only) for 750 ms, we could not do the same because the target was present in the initial portion of our stimuli—if the first portion of the display appeared for 750 ms, the target would pop-out on all trials and there would be no partial pop-out trials to examine. Therefore we used a set of shorter SOAs (durations for the first portion of the display) in addition to the control conditions (described below).

2.1. Method

2.1.1. Observers

Authors EO and RP, and observers JN and MD, participated in Experiment 1a.

Author EO, and observer MD, participated in Experiment 1b. Both had participated previously in Experiment 1a, and MD had participated previously in Experiment 2. A third observer, AF, who had not participated in either Experiment 1a or Experiment 2, participated in Experiment 1b. All had normal or corrected-to-normal vision, and normal colour vision as measured by Ishihara plates.

2.1.2. Equipment

The experiments were run on a Macintosh G3 computer, using MATLAB software and Brainard's (1997) Psychophysics Toolbox routines. The monitor was calibrated for accurate presentation of the stimulus colours using a Minolta Chroma Meter CS-100 and the technique described by Olds, Cowan, and Jolicoeur (1999a). The refresh rate of the monitor was 75 Hz.

2.1.3. Stimuli

The trial began with the presentation of a fixation cross for 400 ms. For the first trial, the fixation symbol was a "+"; it was also a "+" following trials in which the observer responded correctly. Following trials where the observer made an error, the fixation was a "−". After the fixation symbol disappeared the screen was blank for 400 ms.

The first portion of the display consisted of 18 coloured disks which were equiluminant with the gray background (20 cd/m^2, background chromaticity coordinates $x, y = 0.327, 0.332$; *CIELuv* coordinates 92, 0.207, 0.472). The initial D1 distractor disks were a pinkish-orange colour. [1] On 50% of trials, the orange target replaced one of the distractor disks (i.e., there were 17 distractors and one target). The target's chromaticity coordinates were $x, y = 0.416, 0.364$ (target *CIELuv* coordinates were 92, 0.255, 0.501). Following a variable delay (SOA), the display disappeared—the entire screen became the same gray as the background had been—for 107 ms (Experiment 1a) or for 253 or 507 ms (Experiment 1b). The SOAs, which indicate the duration for which the first portion was displayed, were 0, 53, 107, 213, and ∞ ms (note that an SOA of "∞ ms" means that the second set of distractors never appeared). After the 107 ms gray screen, the second portion of the display was presented. This second portion consisted of all the items from the first portion of the display, plus 18 yellowish-orange (D2) distractors. The second portion of the display remained on the screen until the observer responded (by pressing a key marked "Y" to indicate target presence or a key marked "N" to indicate target absence).

The coloured disks measured 8 mm in diameter, which at a distance of 60 cm subtended approximately 0.75° visual angle. The 36 disks were placed in a virtual 6×6 array (7.6° across). On each trial each disk position was perturbed up to one-seventh of a disk diameter both horizontally and vertically. The target could appear in any of the 36 positions except for the four corners.

2.1.4. Procedure

In Experiment 1a, trials with different SOAs were presented intermixed. In Experiment 1b, trials with different SOAs, and with different gray-screen durations, were presented intermixed. In each session of Experiment 1a, 10 practice trials preceded each set of 320 experimental trials. All observers performed four sessions, for a total of 1280 experimental trials, except for observer EO, who performed three sessions, for a total of 960 experimental trials. In each session of Experiment 1b, 10 practice trials preceded each set of 640 experimental trials. Each observer performed two sessions, for a total of 1280 experimental trials each. Observers were given a self-paced break every 50 trials.

Observers, seated in the darkened testing room, sat so that their eyes were approximately 60 cm from the computer monitor; however, head position was not controlled. Previous work has indicated that eye movements are not useful for successful pop-out (Olds et al., 2000b, showed that the perceptual components of pop-out search are completed in roughly 200 ms for stimuli similar to the current stimuli, which is too short for eye movements to help). However, eye position was not controlled and it is likely that eye movements were made by observers when difficult search was required.

All observers had participated in an experiment similar to that of Olds et al. (2000b, Experiment 2) (as illustrated in Fig. 1(a)), which is not reported here, before participating in any of the present experiments.

2.2. Results

For trials in which the observer responded correctly, RT outliers more than three standard deviations away from the mean were removed from consideration, separately for target-present and target-absent trials, and for different SOAs. These were generally long RTs. For Experiment 1a, this procedure resulted in the removal of 1.7%, 0.9%, 1.5%, and 1.5% of RTs for observers EO, JN, MD, and RP, respectively. For Experiment 1b, this procedure resulted in the removal of 1.7%, 2.1%, and 1.7% of RTs for observers AF, EO, and MD, respectively. Fig. 2(a) displays the RTs and error rates, averaged across the four observers, for Experiment 1a. Fig. 2(b) and (c) display RTs and error rates for Experiment 1b, separately for the two gray-screen durations. Error rates were low so we focus on RTs. Target-present RT decreased as SOA increased from 0 to ∞ ms, from 1485 to 625 ms, in Experiment 1a, and from 1621 to 586 ms, in the two conditions of Experiment 1b averaged together. This decrease was expected given that the first portion of the display afforded pop-out search. Target-absent RTs decreased with increasing presentation duration as well, but RTs for the intermediate SOAs that we tested did not reach pop-out values (values for $\mathrm{SOA} = \infty$). [2]

We aimed to measure how much difficult search was occurring at each SOA. To do this we examined the RT distributions for each SOA more closely. We characterized each RT distribution by four numbers: mean RT, mean of the squared RTs, mean of the cubed RTs, and mean of RT^4. These descriptors are the first four moments of a distribution (the first moment is mean RT, the second moment is mean (RT^2), etc.). We calculated proportion difficult search based on these moments. Fig. 3(a) shows proportion difficult search (λ) calculated for the first four moments of the RT distribution for each SOA, for Experiment 1a. See Olds et al. (2000a,b) for a full description of this calculation. Briefly, for each individual observer, the proportion of difficult search trials is 1.0 at $\mathrm{SOA} = 0$, the difficult search control

[1] The exact colour was determined individually for each observer, using a procedure mentioned in Olds, Cowan, and Jolicoeur (1999b); the target colour was in between the two distractor colours in colour space, and they all lay on the same line in colour space. The two distractor colours were chosen to be relatively different from the target for less sensitive observers and somewhat more similar to the target for more sensitive observers.

[2] We refer to the $\mathrm{SOA} = \infty$ condition as "pop-out" search because of the observers' fast performance and because other work in the lab has shown, with the same stimuli, a very small effect of set-size on RTs for $\mathrm{SOA} = \infty$ (much smaller than the effect for $\mathrm{SOA} = 0$).

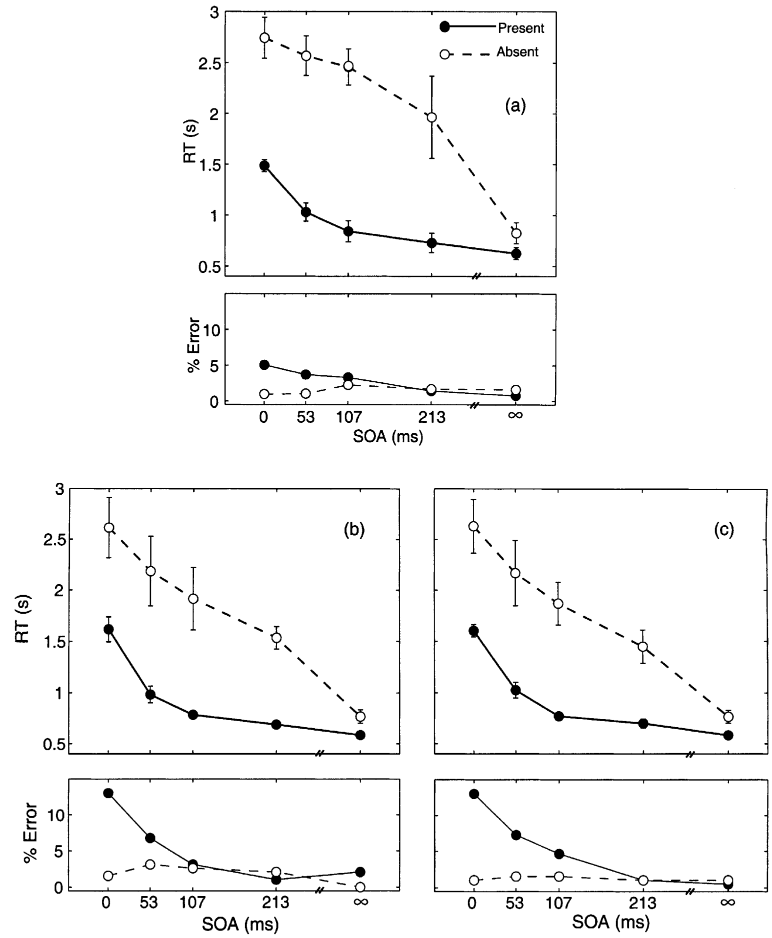

Fig. 2. (a) Experiment 1a: RT and percent error versus SOA, averaged across observers, plotted separately for target-present and target-absent trials. Errorbars represent one standard error below and one standard error above the mean. (b,c) Experiment 1b mean RT and error rates, (b) for gray-screen duration of 253 ms, and (c) for gray-screen duration of 507 ms.

condition—there are no pop-out trials in that condition, so the RT distribution reflects 100% difficult search trials. Proportion difficult search is 0.0 at SOA $= \infty$, the pop-out control condition (by definition). In Fig. 3(a), for each observer the triangles show how mean RT changes from difficult search RT (SOA $= 0$, where λ is 1.0) to pop-out RT (SOA $= \infty$, where λ is 0.0), with increases in SOA. For example, for observer MD, at SOA $= 53$, mean search RT is about 40% of the way in between that for pop-out search and that for difficult search (e.g., in Fig. 3(a) observer MD's SOA $= 53$ triangle is at approximately 0.4 proportion difficult search). The same holds for the other curves included in this graph: the squares illustrate how proportion difficult search, as measured by (mean RT)^2, decreases as a function of SOA. The observers all show the same basic pattern: λs derived from higher moments approach their pop-out values faster than λs derived from lower moments (i.e., the circles are below the triangles).

If the mechanisms responsible for pop-out and difficult search operated independently, the RT distributions for the intermediate SOA conditions would simply be linear combinations of the two control RT distributions (SOA $= 0$, SOA $= \infty$). That is, the mechanisms responsible for pop-out would detect the target (or determine that the target was absent) on some trials, but on the remaining trials pop-out would be interrupted before detecting the target and therefore the slower processes responsible for difficult search would have to detect the target. If this were the case, the λs derived from the four moments would all coincide (i.e., triangles on top of circles, etc.), for each intermediate RT distribution. That the λs do *not* coincide at each SOA indicates that the two mechanisms are *not* independent—they interact.

More specifically, Fig. 3(a) illustrates that this interaction is facilitatory rather than inhibitory—the mechanisms responsible for pop-out assist the mechanisms responsible for difficult search. The higher moments reflect properties of the tails of the distributions (generally the right tail, in RT distributions). The pattern in the λs indicates that the right tail of the distributions shrinks, with increasing SOA, faster than the mean does—therefore, something is speeding up the slowest

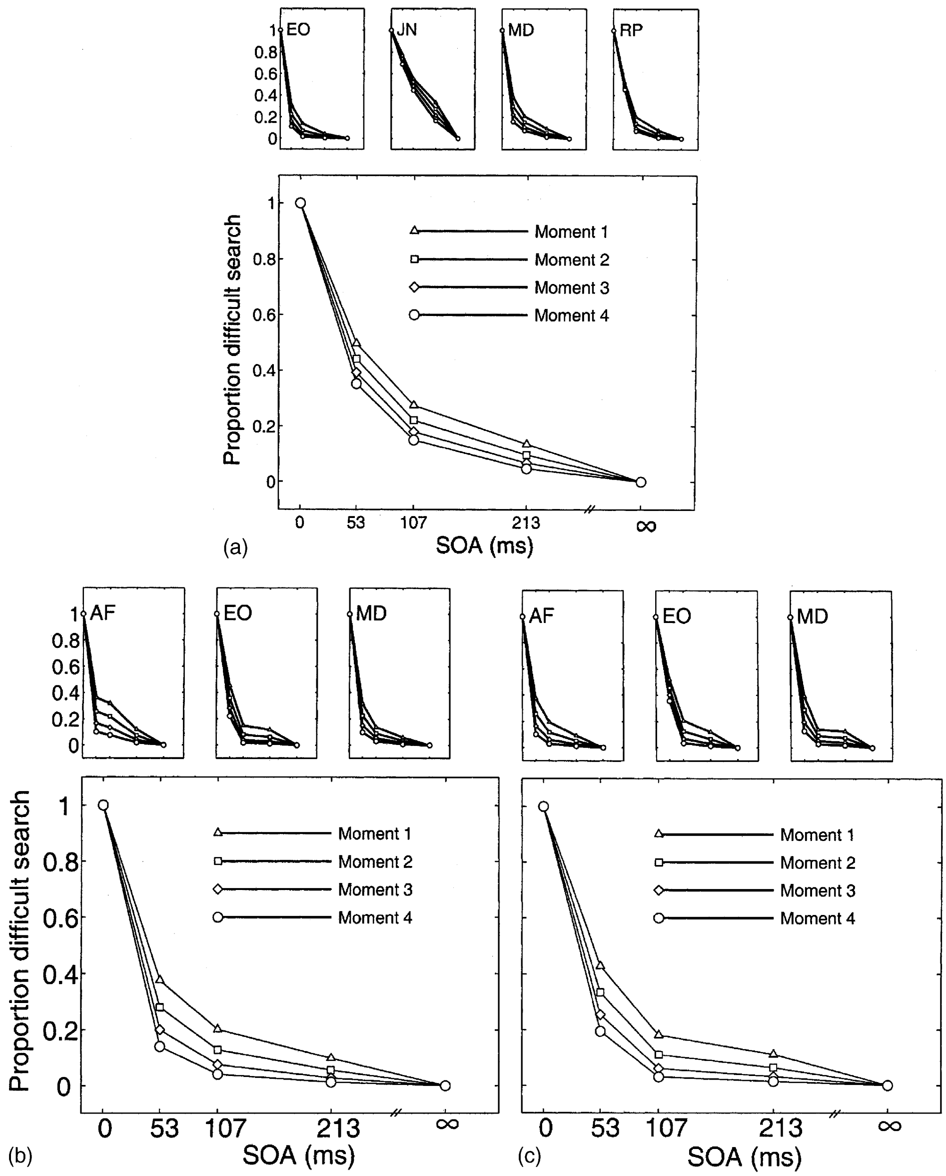

Fig. 3. (a) Experiment 1a: proportion difficult search (λ) plotted against SOA, plotted separately for the first four moments of the RT distributions. Top panels show data for individual observers, bottom panel shows the average plot which is created by averaging the four individual plots. (b,c) Experiment 1b proportion difficult search (λ), (b) for gray-screen duration of 253 ms, and (c) for gray-screen duration of 507 ms.

trials. Completed pop-out cannot be wholly responsible for this speed-up (if it were, this would be reflected in mean RT—simply more RTs on the order of 500 ms—as well as in the tail of the distribution).

It is possible to discern this effect less quantitatively by examining the RT distributions directly. The simple cartoon distributions in Fig. 4(a) illustrate how the intermediate SOA condition RT distributions would look if pop-out and difficult search did not interact. The top panel of Fig. 4(a) is a simplified difficult search RT distribution; the bottom panel is a simplified pop-out RT distribution. Each intermediate "distribution" (middle panels) has been created by sampling from each control distribution in different proportions (i.e., simply combining scaled copies of the two control distributions). Fig. 4(b) shows the actual RT distributions for one observer. Comparison of Fig. 4(a) and (b) illustrates that intermediate distributions are not linear combinations of the control distributions. In the intermediate distributions shown in Fig. 4(b), for example that for SOA = 53, one can cover up the RTs that appear to represent successful pop-out (i.e., RTs below around 1 s that would fall within the bulk of the pop-out control distribution at the bottom of the figure). The remaining uncovered set of RTs (the above-1-s RTs for SOA = 53) does *not* look like a scaled copy of the difficult search RT distribution at the top. That is, the non-pop-out RTs in that distribution are not simply difficult search RTs (if they were, they would look like a scaled copy of the difficult search RT distribution). There are simply not

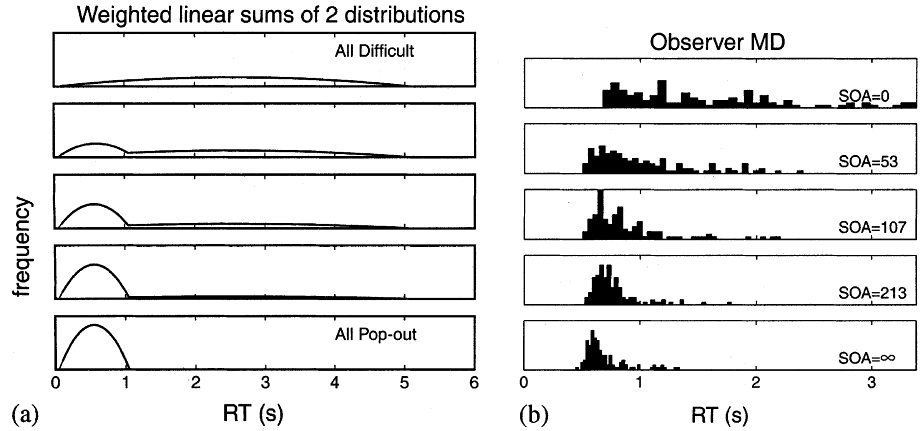

Fig. 4. (a) Simplified illustration of how intermediate-SOA RT distributions would look if they were indeed linear combinations of the two control distributions (the cartoons in the top and bottom panels of the figure). Each intermediate distribution cartoon is created by sampling from the two control distributions in different proportions. (b) Actual RT distributions, for the different SOA conditions, for observer MD in Experiment 1a. The widths of the bins in the different panels have been scaled based on the range of RTs, for best illustration of the shape of the distributions.

enough long RTs (RTs between 2 and 4 s). Olds et al. (2000a) discuss different kinds of combinations of such RT distributions in more detail.

As in Experiment 1a, in Experiment 1b partial pop-out did assist difficult search (see Fig. 3(b) and (c)). The condition that is the most similar to Watson and Humphreys' (1997) Experiment 6 is the condition with the 253 ms SOA followed by the 253 ms gray screen (Fig. 3(b)). In this condition, and in the 507 ms gray-screen duration condition as well, we see that partial pop-out assists difficult search. In Experiment 1b, search assistance did not fade while the search items were not present, despite the fact that the two gray-screen durations were longer than that used in Experiment 1a. The two gray-screen durations, in fact, produced quite similar results. Search assistance appears to last for a relatively long time, rather than decaying quickly, in addition to being robust to disappearances and reappearances of the initial search items.

We approach target-absent trials with caution, because of the more varied range of strategies used (Chun & Wolfe, 1996). Yet we are interested in these trials, given that Olds et al. (2000b) found that the target-absent trials also exhibited the evidence of search assistance that the target-present trials exhibited. That is, for the target-absent RT distributions, Olds et al. (2000b) found that proportion difficult search as calculated by higher moments approached pop-out values faster than proportion difficult search as calculated by lower moments. See Fig. 7 for proportion difficult search calculated for target-absent trials in Experiment 1. Partial pop-out computations did assist difficult search even on the target-absent trials in Experiment 1.

Note that, as mentioned above, these observers participated in an experiment similar to that of Olds et al. (2000b, Experiment 2) (see Fig. 1(a)), before participating in the present experiments. This was necessary because our RT analyses require low error rates (to avoid problems with speed-accuracy tradeoffs), and observers sometimes needed several testing sessions to get used to the somewhat unusual sequence of events in a trial. Observers still tended to make more errors in the short SOA conditions (e.g., SOA = 0, see Fig. 2). A high error in the SOA = 0 condition, however, means that some long RTs are missing from that condition (that is, there would be more slow trials, if the errors were brought down further). This in fact would *increase* the effect that we describe (shown in Fig. 3), so our results actually underestimate search assistance.

2.3. Discussion

Partial pop-out assisted difficult search, despite the blank screen inserted between the operation of the mechanisms responsible for pop-out and the operation of the mechanisms responsible for difficult search. Because Fig. 3 is quite similar to results obtained from other experiments (those in which there was no interruption between the first and second portion of the display; Olds et al., 2000a,b,c, 2001), we can conclude that the information did not decay over the 107 ms. Note the difference between this result and that of Watson and Humphreys (1997, Experiment 6), who found that visual marking was eliminated if the display disappeared between the two portions. The continuous presence of the search items is not required for search assistance.

Partial pop-out assisted difficult search on target-absent trials as well as on target-present trials. Olds et al. (2000b) interpreted this kind of result as indicating that partial pop-out must assist difficult search by indicating something about where the target is not (otherwise the assistance would not occur on target-absent trials) as well as (or instead of) indicating something about where the target is, which can only occur on target-present trials. It could also indicate where the target could be, i.e., the initial item locations (Olds et al., 2001). The results of Experiment 1 indicate that even when the display is interrupted between the gathering of pop-out-based information, and the difficult search that is required for the second portion of the display, this information about where the target is not, or could be, is still useful to difficult search.

It is likely that some iconic representation of the first portion of the display persisted through at least some of the blank screen. This would result in a longer effective duration for pop-out processing to operate, for all the intermediate SOAs (it would not affect the control conditions). Therefore, if the interruption did not disrupt search assistance (which it appeared not to do), this would be equivalent to adding up to 107 ms to each effective SOA (i.e., 160, 214, and 320 ms, instead of 53, 107, and 213 ms). Previous results have shown the longer SOAs simply produce more successful pop-out, not more search assistance, so persistence of the first portion of the display is not a problem for interpretation of these results.

3. Experiment 2

The difference between the results of Experiment 1 (search assistance despite an intervening blank screen) and those of Watson and Humphreys' (1997) Experiment 6 (no marking when a blank screen intervened) might indicate that the mechanisms responsible for visual marking are not involved in search assistance. However, there is another possible explanation. Because Watson and Humphreys' (1997) display items were not equiluminant with the background, their displays underwent a luminance change when the second portion of the display appeared. That luminance change could explain why Watson and Humphreys' results for interruption with a blank screen (the screen was black and blank when the items disappeared) were different from those of the present Experiments 1a and b (search assistance), even if indeed visual marking and search assistance arise out of similar mechanisms.

Since the present target and distractors were equiluminant with the background, as in Olds et al. (2000a,b), perhaps the change caused by the blank screen was not severe enough to interrupt search assistance. In addition, because the iconic representation of the first portion of the display persists while the screen is blank, observers may search that icon. However, search assistance does not seem to be any greater with a 507 ms blank interval than with a 253 ms blank interval (see Fig. 3(b) and (c)). This suggests that search assistance does not continue or increase but rather stops during the blank interval.

Nevertheless, the severity of this interruption was investigated further. In Experiment 2, all the disks became black in between the first and second portion of the display (Fig. 1(c)). That is, all 36 potential item locations contained black disks for 107 ms (Experiment 2a) or for 253 ms (Experiment 2b). Luminance onsets capture attention, so this temporary luminance change might disrupt processing more than an equiluminant gray screen the same colour as the background (which simply temporarily removed the disks from the display, as the background remained the same colour). Alternatively, perhaps search assistance is robust even to this luminance interruption. Evidence for this possibility is provided by the fact that changing luminance in the display per se does not disrupt search assistance—Olds et al. (2000c) presented oriented black lines on a gray background (thus when D2 distractors were added to the display, there were luminance changes at those "new" locations), and still found search assistance.

3.1. Method

3.1.1. Observers

Author RP, and observers JN, MD, and NO, participated in Experiment 2a. Observers JN, MD, and RP completed Experiment 1a before beginning Experiment 2. Observer NO did not participate in either Experiment 1a or Experiment 1b.

Author RP and observers BW, MD, and MM participated in Experiment 2b. Observers BW and MM had not participated in the other experiments in this paper; observer MD participated in Experiments 1a, b, and 2a before participating in Experiment 2b.

3.1.2. Stimuli

The stimuli were identical to those of Experiment 1a except that during the interruption, instead of a gray screen there was a 6×6 array of black disks, appearing for 107 ms (Experiment 2a) or 253 ms (Experiment 2b) in the coloured disks' locations (Fig. 1(c)). For SOA $= 0$ trials, the black disks appeared before the onset of the difficult display. For SOA $= \infty$ trials, for Experiment 2a, they appeared *after* the observer pressed a key to respond (for Experiment 2b they did not).

3.1.3. Procedure

As in Experiment 1a, 10 practice trials preceded each session of 320 experimental trials. All observers completed four experimental sessions of each experiment, for a total of 1280 trials each for each experiment.

3.2. Results

See Fig. 5 for RTs and error rates for the different conditions of the two experiments. As in Experiment 1, in Experiment 2 RT outliers more than three standard

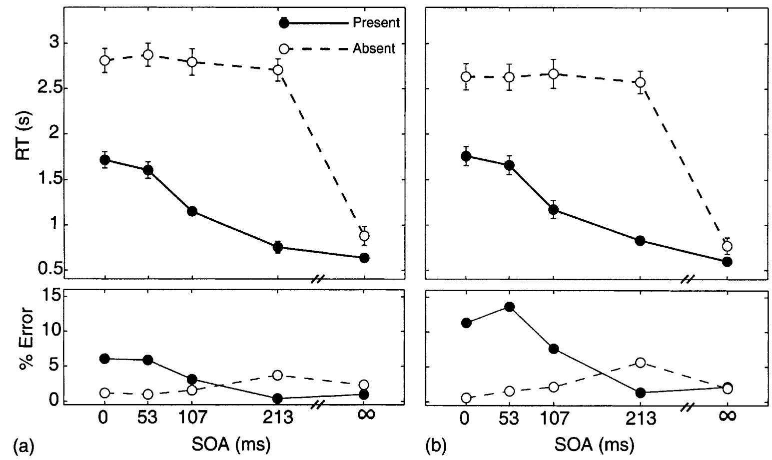

Fig. 5. Mean RT and error rates, versus SOA, for (a) Experiment 2a and (b) Experiment 2b.

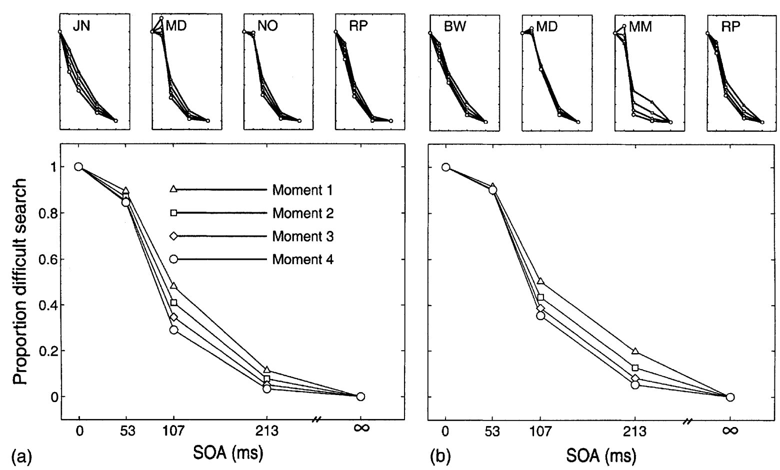

Fig. 6. Proportion difficult search (λ) versus SOA, for the first four moments, for (a) Experiment 2a and (b) Experiment 2b.

deviations away from the mean were removed, resulting in the removal of 1.3%, 1.3%, 1.2%, and 1.3% of RTs for observers JN, MD, NO, and RP, respectively (Experiment 2a), and 2.3%, 1.5%, 1.0%, and 2.1% of RTs for observers BW, MD, MM, and RP, respectively (Experiment 2b).

Percent error was again low (although target-present errors were higher for Experiment 2b than for Experiment 2a) so we concentrate mainly on RT. As in Experiment 1, target-present RT decreased as SOA increased from 0 to ∞ ms (from 1715 to 637 ms for Experiment 2a; from 1758 to 600 ms for Experiment 2b). Target-absent RT did not decrease much from SOA $= 0$ levels (over 2.5 s) until the SOA $= \infty$ condition. That is, for the intermediate SOAs, target-absent performance was as slow as for the difficult search control condition, despite the time spent with the pop-out display (unlike in Experiment 1; see Fig. 2).

Fig. 6 displays the λs calculated from the different moments in Experiment 2. As in Experiments 1a and b, partial pop-out assisted difficult search, on these target-present trials, although possibly less so for the shortest SOA. However, unlike in Experiment 1, in Experiment 2 partial pop-out computations did not assist difficult search on the target-absent trials (see Fig. 7(d) and (e)). [3]

[3] Yantis and Gibson (1994) showed that with a 100 ms disappearance and reappearance, an object becomes new and captures attention in a search task (their stimuli were not equiluminant with the background and thus item disappearance and reappearance both caused luminance changes). In the current Experiment 2, the 107 ms disappearance (with luminance change) of all the objects should therefore be enough to cause *all* of the items in the difficult portion of the display to be new and to attract attention, erasing prioritization for the initial items. However, on the contrary, some information from the first portion of the display *was* carried over to processing of the second portion (search assistance for target-present trials). This may be because the items can be seen as temporarily changing colour (to black) instead of disappearing, in Experiment 2.

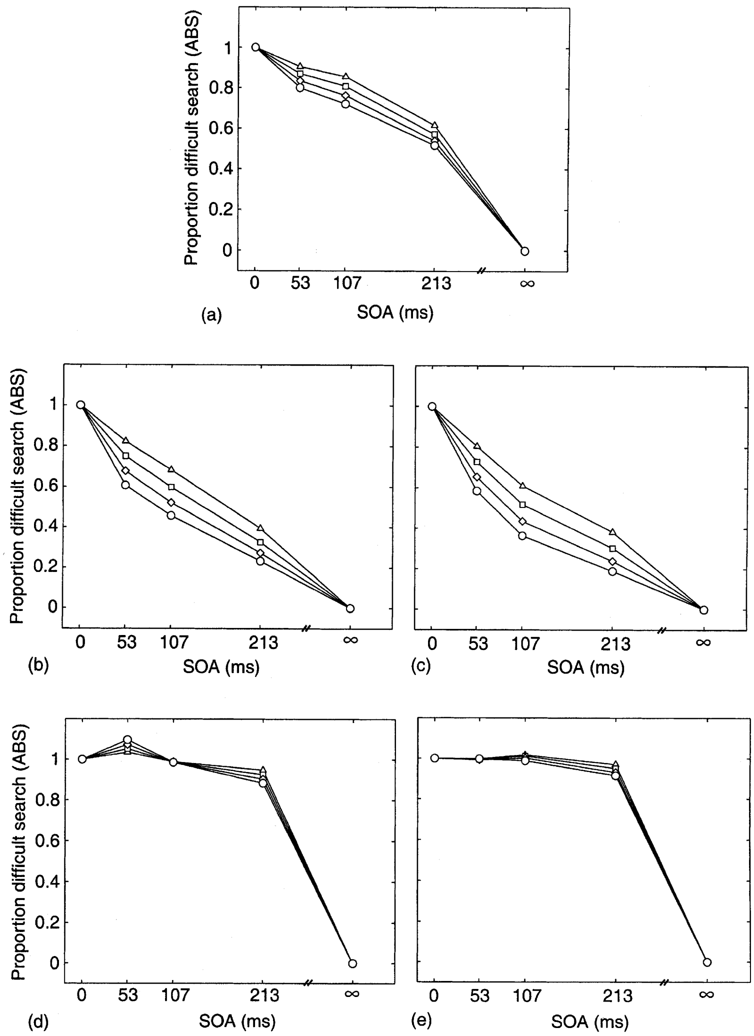

Fig. 7. Target-absent λs plotted against SOA, for (a) Experiment 1a, (b) Experiment 1b, gray-screen duration of 253 ms, (c) Experiment 1b, gray-screen duration of 507 ms, (d) Experiment 2a, and (e) Experiment 2b.

3.3. Discussion

Search assistance may involve information about where the target is on target-present trials, and information about where the target is not on both target-present and target-absent trials (Olds et al., 2000b); the mechanisms responsible for representing these two different types of information may be dissociable. As mentioned above, the latter type of information, information about where the target is not located, could be provided by the mechanisms responsible for visual marking. Visual marking is known to be disrupted by item disappearance accompanied by luminance change (Watson & Humphreys, 1997). Therefore, Experiment 2 was based on the idea that whatever is disrupted by luminance changes might be caused by visual marking.

In Experiment 2, partial pop-out did not assist difficult search on target-absent trials, while it did on target-present trials. These results suggest that the mechanisms responsible for transmission of information about where the target is not located are indeed vulnerable to luminance changes, while those encoding target location are not. Under normal conditions without luminance interruption (Experiment 1), the mechanisms responsible for information about where the target is not are intact, and thus search assistance occurs for target-absent trials as well as for target-present trials. However, with luminance interruption (Experiment 2), partial pop-out may not be able to transmit information about where the target is not, and perhaps can only transmit information about where the target is (which only exists on a target-present trial), and thus in Experiment 2 search assistance only occurred for target-present trials. In addition, search assistance was not consistent across observers for the shortest SOA target-present trials (see Fig. 6). Normally, on target-present trials, search assistance could involve both information about where the target is and information about where the target is not.

However, in Experiment 2 it is possible that one of these sources of information was disrupted, and this could have led to the apparent lack of assistance for the shortest SOA.

There is another possible explanation for the difference between the results of Experiment 2 and those of Experiment 1: luminance afterimages could have made observers less confident. Observers use a wider range of strategies for target-absent trials than for target-present trials (Chun & Wolfe, 1996), so RTs may be more variable for target-absent trials and the relevant processes may be more susceptible to things like afterimages. Evidence supporting this hypothesis is provided by the high intermediate-SOA target-absent RTs in Experiment 2 as compared to Experiment 1 (Fig. 5 versus Fig. 2). To consider this possibility further we examined the RTs in the control conditions.

For target-present trials, mean RT for target detection in the SOA $= \infty$ condition, for Experiment 1a, Experiment 1b (averaging over the two gray-screen durations), Experiment 2a, and Experiment 2b, was 625, 586, 637, and 600 ms, respectively. Mean RT for correct target-absent trials for these experiments was 823, 758, 880, and 771 ms, respectively. These numbers were not expected to be very different from each other (i.e., target-present mean RTs were all expected to be in the same range), because at this SOA the second portion of the display never appeared (and the gray or black interruption between the first and second portions did not appear before observer response). Since all SOAs were presented intermixed within each experiment, though, uncertainty or noise based on intermediate-SOA trials could have affected performance at all SOAs; however, the numbers do not show strong evidence for this possibility.

The SOA $= 0$ control condition, unlike the SOA $= \infty$ control condition, was different for Experiment 1 and Experiment 2—in Experiment 2 the difficult display was preceded by the 107 ms black disks, for purposes of comparison with the intermediate SOA trials (for this SOA $= 0$ condition, RT was measured from the onset of the informative display with the coloured target and distractor disks). Mean RT for target detection in the SOA $= 0$ condition was 1485, 1621, 1715, and 1758 ms, respectively, for the four experiments. Mean RT for target-absent trials was 2744, 2643, 2810, and 2635 ms, respectively. Focusing on these target-absent RTs, there does not seem to be a large difference overall between the first two (Experiment 1a and b) and the last two (Experiment 2a and b), in fact this difference is smaller than that for target-present trials (and target-present trials *did* show search assistance in Experiment 2). If luminance afterimages played a large role in search performance, these numbers should be different; thus we do not see strong evidence for an effect of luminance afterimages on our search assistance results for target-absent trials.

In Experiment 1, errors were similar for the two gray-screen durations (Fig. 2(b,c)) and so was search assistance (Fig. 3(b,c)). In Experiment 2, on the other hand, although search assistance looks equivalent for the two black-disks durations (Fig. 6), target-present errors were higher for the longer black-disks duration (Fig. 5). Thus we cannot conclude that duration of luminance change has no effect on performance; it seems to have more of an effect than duration of equiluminant disappearance does.

Note that while the duration of the mask (blank screen in Experiment 1; black disks in Experiment 2) was included in the observer's RT for the intermediate SOA conditions, it was not included for the control SOA conditions. The reasons for this are as follows. In the pop-out control condition, the mask only appeared after the observer's response, if at all. It would not make sense to include its duration in the RT. In the difficult search control condition, in Experiment 2 the black disks did appear before the search stimulus (to control for afterimages) but as there was no useful information in this display, its duration was not added to the difficult search RT. In the intermediate SOA conditions, the mask occurred between the first and second portions of the display—and in addition processing could be occurring, for example an icon could be searched—and thus its duration was included in overall search RT.

It could be argued that including mask duration in the intermediate SOA RTs, but not in the control RTs, invalidates the comparisons between the distributions (described in the Results section). That is, perhaps the intermediate-SOA RTs will be unnaturally lengthened. It is not clear, however, how this change would skew the pattern in the data. Imagine taking the RT distributions from an experiment without a mask (as illustrated in Fig. 1(a)), and adding 253 ms, for example, to each RT of each intermediate distribution (corresponding to the duration of the mask, which is added to each RT in the present experiments). This change could increase or decrease the right tail of the intermediate distribution. It might increase the right tail: if the RTs started out fairly long (e.g. 3 s), they would now become a bit longer and might increase their similarity to pure difficult search RTs. As explained above, we conclude that partial pop-out helps difficult search because the right tail is too *short* in the intermediate RT distributions, relative to the control distributions. Therefore if our data include an artificial lengthening of RTs in the intermediate distributions, this is simply weakening any results—meaning that we have measured an *under*estimation of search assistance, and search assistance is even stronger than our current results indicate. However, 253 ms added to each RT could also decrease the relative size of the right tail. If the RTs started out relatively short (e.g. 700 ms, which might fall within the range of control pop-out RTs), then this change would take them out of the range of pop-out RTs, and make them look like some process intermediate between pop-out and difficult search. That would mean that our results *over*estimate the amount of search assistance going on. And, of course, intermediate effects could be imagined.

Although we thought it highly implausible that no processing whatsoever was going on during the mask presentation, we considered a strong version of the concern described above. We focused on trials for which the observer's response occurred at least 200 ms after the mask disappeared—only then can it be argued that the full mask duration has been added to processing time, before motor response has been initiated. For a given SOA, the easy portion of the display was present for SOA ms, so the mask disappeared after (SOA + mask-duration) ms had passed. For each intermediate-SOA RT distribution in Experiment 2, for example, for each RT, if it was longer than (SOA + mask-duration + 200 ms), we subtracted the mask duration from it (i.e., for an SOA of 107 ms, if the RT was greater than $107 + 107 + 200$, then 107 ms was subtracted from it) because this time represented time spent looking at the mask. Again, this only was done for the intermediate SOA conditions, because the control conditions' RTs did not have mask duration included in them.

For each experiment, this drastic change only weakened the pattern in the target-present λs somewhat, in particular for SOA = 213 ms. It weakened the pattern in that each SOA = 213 RT distribution became almost identical to the corresponding pop-out distribution (because the longest RTs had been shortened); and thus the λs for the four moments coincided (as they do for SOA = ∞). This drastic change had virtually no effect on the target-absent λs. Given that this manipulation, subtracting the entire mask duration from the RT, was probably too strong (it is very unlikely that no icon could be searched whatsoever, especially in Experiment 1), the fact that the results still generally held indicates that the concern mentioned above is not a problem for the interpretation of our results.

4. General discussion

These experiments set out to determine several things. First, in Experiment 1 we sought to measure whether search assistance would decay over delays of up to 500 ms. It did not. Search assistance appears to be quite robust, given that it persists despite disappearance and reappearance of the items.

Second, in Experiment 2 we added a luminance change (onset and offset of black disks) to the interruption in order to mimic more closely Watson and Humphreys' (1997) Experiment 6. For target-present trials, search assistance persisted despite this luminance change, but for target-absent trials, search assistance was disrupted. These results are consistent with a role for visual marking in search assistance, particularly on target-absent trials. Note that it likely plays a role on target-present trials as well, indicating on all trials a set of locations where the target has been determined not to be. Finally, it is still possible that search assistance involves, in part, information about the locations of the initial items (as mentioned in Section 1), and other work in our lab is currently investigating this possibility.

The Guided Search model (Wolfe, 1994; Wolfe, Cave, & Franzel, 1989) provides one possible framework for understanding how partial pop-out could assist difficult search. In Guided Search, information from feature search guides a serial difficult search process, by transmitting activations that reflect the match between each item and the desired target. Items with high activations will be serially considered earlier than those with lower activations. In the first portion of our displays, activation of potential targets (and perhaps suppression of badly matching items that are probably distractors) can begin to build up. Even if pop-out processing is interrupted and difficult search must proceed during the second portion of the display, difficult search can still use that initial information to prioritize items for serial consideration (assuming that the information does not fade too quickly, and the present set of experiments indicates that it does not). This purely Guided Search-based account does not, however, explain why search assistance did not occur for the target-absent trials of Experiment 2—perhaps it must be combined with visual marking to account for all of our data.

It makes sense that, at the very least, some of the mechanisms responsible for visual marking could be involved for target-absent trials—one must determine that the target is not in any location. In addition, since the visual system does not know whether the trial is a target-absent trial or a target-present trial until the end, this mechanism would have to be used on target-present trials as well. Further research is necessary to confirm the role of the mechanisms responsible for visual marking in search assistance—is there a complete overlap in mechanism or is it only some of the component mechanisms from marking that are also involved in search assistance? For example, current experiments in the lab are investigating whether search assistance is disrupted by a capacity-loading rapid serial visual presentation task (as Watson and Humphreys (1997), Experiment 8, showed marking to be).

The work of Watson and Humphreys (1997, 1998, 2000) has indicated that people can prioritize selection for *new* items—in their experiments, the target always appeared in the second portion of the display and thus selecting new items made search more efficient. The present work shows that people can prioritize selection for *old* items, when new distractors are added to a display. In these experiments the target always appeared in the first portion of the display and thus selecting old items and ignoring new items was adaptive. That is, the visual system is flexible and can adapt to the demands of particular situations.

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